Hot Off the Printer

BY JUSTIN BINDER, PENG, AMANDA DODGE, DAVE ECKMANN, SE, PE, FAIA, ELOY RODRIGUEZ, AND RYAN SHERMAN, PE, PHD

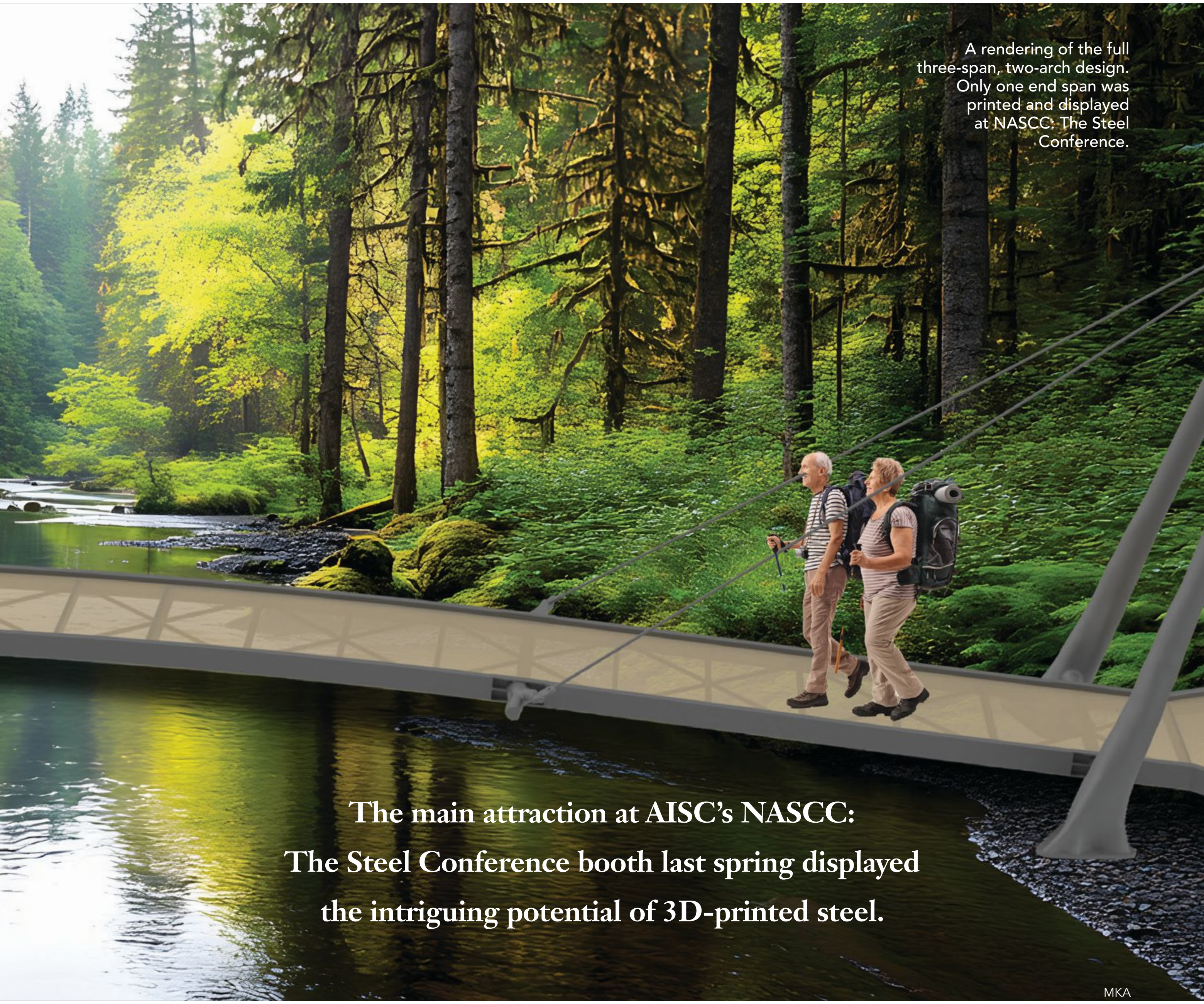
ONE OF THE MOST EXTENSIVE 3D-printing steel bridge projects in the U.S. was constructed to be an exhibit. Not in a museum or on display in a real-world setting, but as a main attraction at 2025 NASCC: The Steel Conference in Louisville, Ky.

AISC made a 36-ft-long 3D-printed steel pedestrian bridge the centerpiece of its booth at the conference as a showcase for the type of connections and geometries possible with steel 3D printing. Following its display at The Steel Conference, it became part of a load testing research project that ventured into new territory and remains ongoing.

Steel additive manufacturing (AM), otherwise known as 3D printing with steel weldment, is a new tool in an engineer's toolbox that opens the door to new design possibilities. The AISC bridge demonstrates AM's potential when used in combination with standard structural shapes. AM can be most beneficial when complex geometries are not physically possible to construct with traditional structural sections, or when a desired component or connection geometry is not available as a standard rolled shape.

AISC engaged a group of AM industry leaders to design and construct a full-scale structure for display as proof of concept for AM's design, fabrication, and aesthetic possibilities. While many proof-of-concept ideas were discussed, a pedestrian bridge with a 3D-printed arch was chosen because it is a horizontal structure that can be easily seen, touched, and experienced in an exhibit environment. The full design is a modular 50-ft structure that could be erected and disassembled in segments, but only one end span of the bridge was built for display at The Steel Conference. The 50-ft design is a three-span bridge, with the middle span supported by two end spans with backstays.

Because the pedestrian bridge is an educational exhibit and not designed for a specific site, a hypothetical river within a wooded site was selected as its home. The bridge aimed to integrate organic

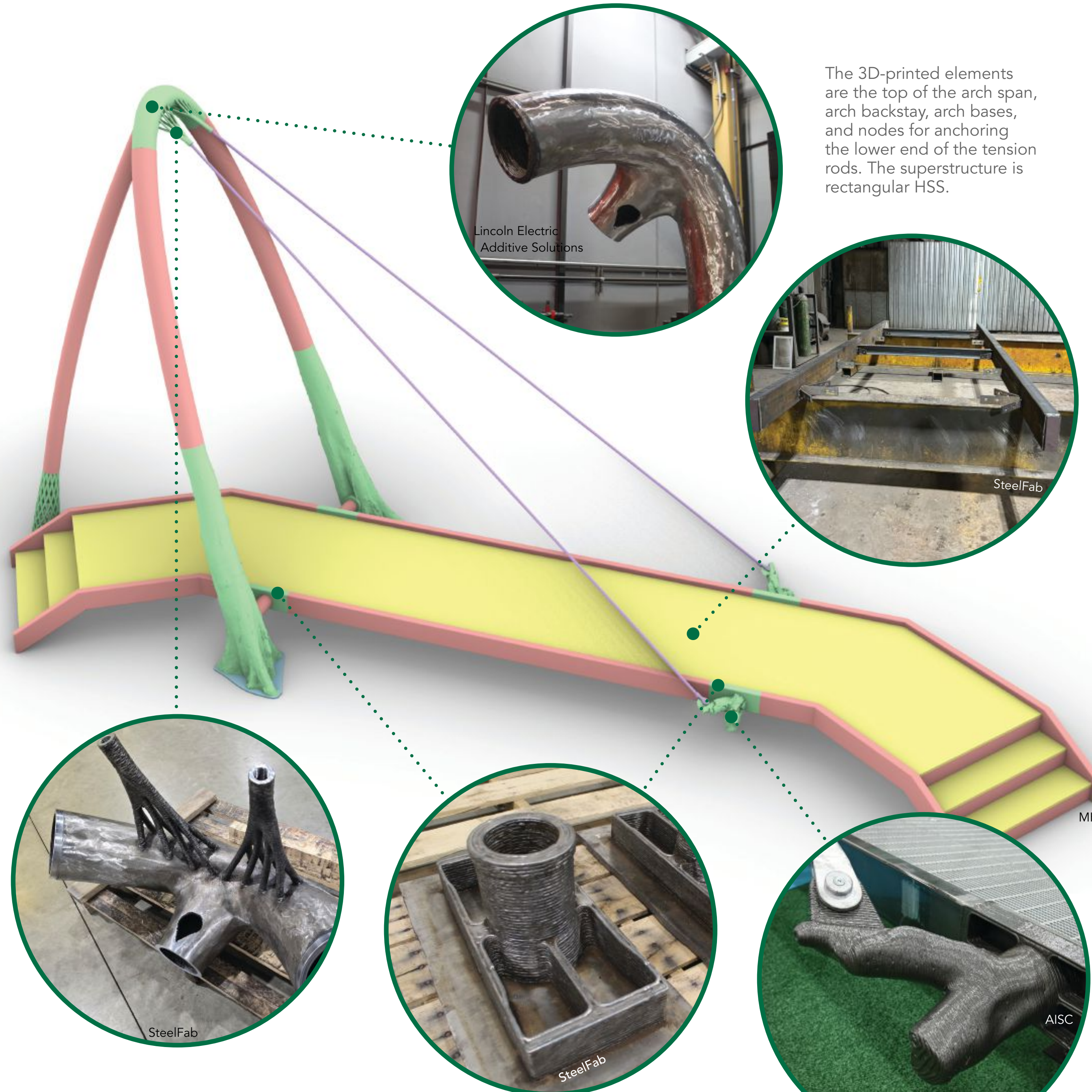


A rendering of the full three-span, two-arch design. Only one end span was printed and displayed at NASCC: The Steel Conference.

forms found in the forest into a slender steel bridge. Canted arches that anchor each end of the bridge symbolize leaning trees at the river's edge. Steel tendrils extend from the arches, morphing into steel tension rods that gracefully support the curved bridge deck. Arch backstays with bases that resemble wetland reeds disappear into the forest floor. Temporary supports below the bridge were added to meet the exhibit hall floor loading limitations and because the arch's backstay couldn't be bolted to the exhibit floor. Without the temporary support, the backstay would be in tension and need to be anchored to a foundation.

Tapering branches and tree trunks from actual trees were scanned and converted into digital files. As a result, lead designer Magnusson Klemencic Associates' vision of tree trunks morphing into bent 8-in.-diameter round HSS could be printed and incorporated as structural components within the bridge. The 17-ft-high, 10-ft-wide arch's narrow geometry was achieved by 3D printing the top of each arch to a tighter radius than possible if using advanced HSS bending procedures. The printed arch base and top components were then welded to standard HSS bent to varying radii. To show various finishing options, the tree trunk arch bases were left as printed, and the top of the arch was ground smooth. Ends of printed shapes attached to standard structural shapes were milled smooth.

The bridge was analyzed using a conventional structural analysis program. The analysis model defined the tapered arch geometry and associated wall thicknesses. Components were optimized and required only the minimum amount of material. Since only a third of the bridge was going to be constructed for the exhibit hall, several load combinations for the full bridge and partial bridge were analyzed. The primary structure forces were then shared with the specialty engineers responsible for analyzing and reinforcing the individual AM components.



The 3D-printed elements are the top of the arch span, arch backstay, arch bases, and nodes for anchoring the lower end of the tension rods. The superstructure is rectangular HSS.

Print the Parts

AISC associate member CAST CONNEX engineered the AM parts, including detailed part shaping, connection calculations, finite element analysis (FEA), and development of manufacturing shop drawings. The AM part design process began with receipt of the architectural and engineering design inputs, rough 3D models representing the aesthetic design intent, and loading from the global structural analysis model.

For each part type, CAST CONNEX prepared part models ready for AM manufacturing by working collaboratively with the design team (MKA), manufacturer (Lincoln Electric Additive Solutions), steel fabricator (SteelFab), and various machine shops to develop the geometries. It considered a multitude of design constraints: engineering (stiffness and strength); architectural (part shaping, surface finish); AM manufacturing considerations (minimum printable thickness, limits on overhangs); and fabrication and erection decisions (choice of shop-welded and field-bolted joints).

The AM components were engineered using a combination of conventional code-based calculations considering typical connection limit states as outlined in the AISC *Specification for Structural Steel Buildings* (ANSI/AISC 360-22). FEA was leveraged to analyze the complex 3D shapes. Load combinations were extracted from the global structural analysis model and applied as boundary conditions to local 3D FEA models of each connection type. These models confirmed that the load path through the connections met the design intent and that the magnitude of any stress and strain risers within the parts were within code-consistent acceptance criteria. Stiffness studies were also performed to ensure that the AM components were not more flexible than the frame elements used in the structural analysis of the overall bridge structure.

The final connection geometries exemplify AM's ability to integrate functional structural details into single components that simultaneously solve architectural-, structural-, fabrication-, and erection-related challenges. The following examples highlight some of these unique connection features:

Incorporating build plates into final part geometry. The 3D printing build plates upon which the layers of weld are deposited were intentionally incorporated into the final design of the parts (the base plates for the trunk and spiral components, and the connection side wall for the deck nozzle and deck branch connections). As the build plates were susceptible to warping under the heat of welding, CNC machining of the underside of the plates after printing was used to ensure dimensional conformance of the final components.

Internal AM features for structural stiffness and strength. Initially, the trunk component was conceptualized as a thin-shelled connection that transitioned from the HSS wall thickness into the tree-like curving geometry at the base plate. FEA highlighted the need for increased connection stiffness at the interface of the primary member to the secondary HSS connection. Thus, an internal stiffener feature was incorporated into the final part geometry, which addressed the part stiffness issue while minimizing the weight of additional material. Similarly, the arch component was internally thickened in the overlapped connection region to improve stiffness and strength, efficiently adding material only where it was required.

Accommodation of welded and bolted connections. AM's freedom of geometry was leveraged to enable the desired shop fabrication and field erection scheme. Connections featuring shop-welded joints were created by printing the connection nozzles with extra stock material that was subsequently CNC-machined to the required location and orientation, ensuring the final AM-connection-to-HSS welded connections could be ground smooth (for example, the bridge's spiral connection welds).

Additionally, the AM manufacturing process enabled the use of innovative bolted connections. The deck nozzle and deck branch connections feature a readily printable open section with pockets for two structural bolts designed to interface with a fabricated bolted connection. The arch connection incorporated a similar bolted end plate connection where the AM part featured a teardrop-shaped hand hole for bolt access, with the teardrop shape proportioned based on minimum overhang requirements associated with the printing process.

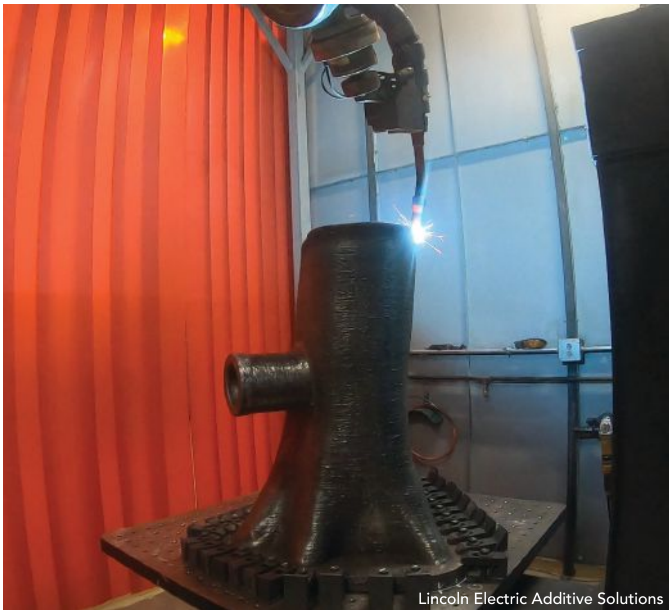
Design for sequential manufacturing. Production documents, including 2D drawings and 3D model files, were created to depict the as-printed and as-machined stages of manufacturing. These documents specify dimensional tolerances for both stages and guide balancing of the as-printed component in machining fixtures, accounting for 3D printing dimensional variations and base plate warping. For the arch component, shop drawings detailed additional surface grinding and tendril printing steps to ensure accurate positioning of drilled and tapped holes for the tension rods.

Lincoln Electric Additive Solutions (LEAS) carried out the additive manufacturing for the project. LEAS specializes in gas metal arc additive manufacturing (GMAAM), also known as wire-arc additive manufacturing (WAAM), where large-scale metal parts are built one weld bead at a time, one layer at a time, until the intended geometry is achieved. The general process involves design for AM, engineering (build strategy determination and path planning), production, and quality.

The collaborative design with CAST CONNEX streamlined the process for the bridge components because LEAS received part models for exactly what needed to be printed with the build strategy already in mind. The robotic systems have the capability to print in multiple directions, or waypoints, to minimize the need for support material and achieve aggressive overhangs. The multi-waypoint capability is possible by fixturing the print on a positioner arm with two degrees of motion to manipulate the parts throughout deposition to maintain depositing layers with gravity. Several of the bridge components used positioner motion to achieve their geometries, including both trunk pieces, the top arch, and deck branches.

The carefully crafted design of each part showcased several WAAM unique capabilities: varying thickness, complex/organic geometries, light-weighted/optimized design, coordinated motion, and integrated build plates. The LEAS production facility has 22 additive systems for GMAAM, and many of the bridge parts were printed in parallel to ensure completion in time for display.

All told, eight parts were printed on five different additive systems. Production for the components took about six weeks with about 750 hours of active print time. Over 2,000 lb of weld metal was used to print the parts, comprised of over 30,000 individual welds. After production, parts were sent to Zimmerman Metals to be partially machined for assembly.



Lincoln Electric Additive Solutions

The tree trunk arch bases were left as printed to show one finishing option. The ends of printed shapes (below) were milled smooth to acccomodate weld preparations and show another finishing option.

Fast Fabrication

Detailing the assemblies was achieved by referencing the CAST CONNEX design model for the AM parts to model the connections for the rest of the members framing into them. The CAST CONNEX team fully detailed the AM parts, not just individually to the post-machined geometry, but also located spatially in the model. The model of the regular structural steel components and the fabrication and erection drawings were provided by H&R Steel Detailing. SteelFab leveraged the model to visualize the unique connections, confirm there would be enough hand access to bolt the members, and splice the assemblies in a way requiring few temporary supports during erection.

During coordination meetings with AISC, SteelFab determined that maximizing the amount of shop-assembled material would be best for the exhibit hall at The Steel Conference, given the limited erection area and timeframe. SteelFab settled on five different shop frames for the bridge that allowed the fabrication team to erect the arch as a self-supporting "tripod" and attach the bridge walkway assemblies and stairs.

Bridge fabrication took about three weeks, starting with processing AM components, tension rods, clevises, and all other hardware. Rolled material was processed by AISC member bender-roller Chicago Metal Rolled Products and shipped early to SteelFab's shop.

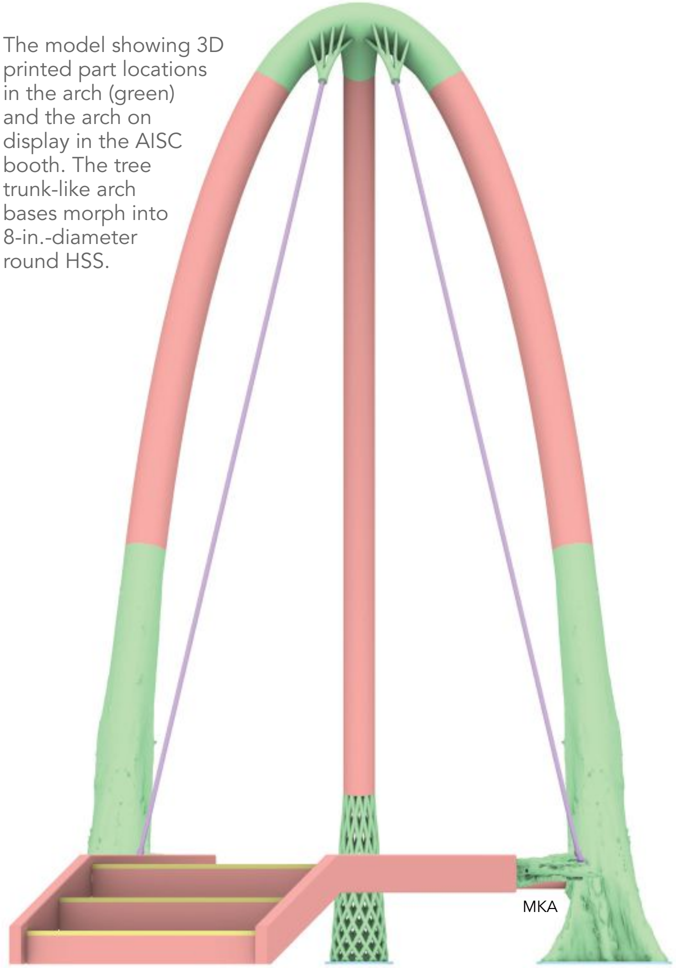
Most of the AM parts' geometries are similar to standard steel shapes, but the top U-shaped AM part was a fabrication challenge. This part was welded to the rolled tubes on two sides, and the rear connection was a through bolt to the tripod's rear leg so it could be more easily taken down and shipped.

The top part's geometry did not have any square faces or planes to use for reference. If fabricators had machined reference scribed lines or markers at the top part's key points and used the model to scribe those same marks on the rolled tubes, fit-up would have been easier to perform, especially on a PJP/CJP welded connection. SteelFab experienced similar challenges when attaching the two trunks to the rolled tubes, but used the bolt holes on the bottom of the base plate to square the part and reference dimensions.

All parts were sand-blasted individually or as finished assemblies, depending on their geometry, and the bridge received a clear coating that does not cover the details in the standard or AM parts but helps maintain the finish. MKA designed all bolted connections to use ASTM A325 hex head bolts, which simplified sourcing the hardware.

Bridge and stair grating were provided by Lichtgitter USA. The design team settled on W11-4 style grating with a serrated surface. The finish was hot-dipped galvanized, and the panels were attached to the bridge using G-Clips to facilitate multiple future assemblies. The bridge girders are 8×3 square hollow structural sections (HSS). All HSS members came from Atlas Tube.

The arch backstay resembles wetland weeds.



The model showing 3D printed part locations in the arch (green) and the arch on display in the AISC booth. The tree trunk-like arch bases morph into 8-in.-diameter round HSS.

MKA

Carrying the Load

Following The Steel Conference, the bridge was transported to the Georgia Institute of Technology for structural load testing on the full 50-ft design. The over-arching goal of the controlled load testing is to demonstrate that metallic additive manufacturing can be leveraged to support and transmit structural loads. The testing is among the first fact-finding projects for a structure that combines AM components and rolled sections intentionally designed as a system.

While AM structures' architectural opportunities are visually striking, the AM demonstration bridge also highlights some under-discussed AM structural advantages. Through controlled load testing, the bridge is expected to show it can support the full design load. Further, the controlled load testing will be used to validate the 3D FEA models CAST CONNEX created during the AM component engineering.

Temporary supports that accommodated conference center floor load restrictions were removed and the bridge was secured to Georgia Tech's reaction floor, creating the full end-span cantilever structure. Tanks placed on the bridge deck will be filled with water to simulate the design live load. At the end of the cantilever, a hydraulic cylinder will be used to apply the total load of the drop-in center span. Instrumentation to measure load, displacement, and strain will be installed throughout the bridge to monitor the AM bridge response. Digital image correlation (DIC) will be used to compare full-field strain measurements with the 3D FEA models of the AM components from CAST CONNEX. Ultimately, the controlled load test results will be physical proof that AM offers a unique structural solution to the steel industry.

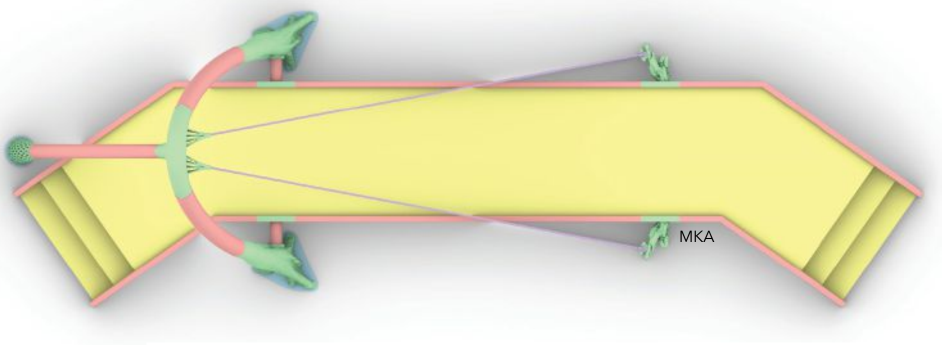
Looking Ahead

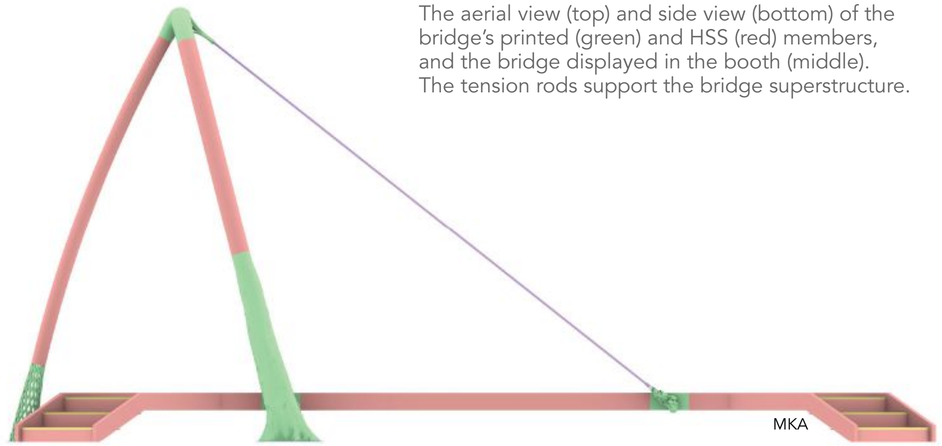
The AISC AM bridge demonstration project has yielded numerous important lessons that will help advance large-format metallic AM toward in-service implementation for structural engineering applications. After the demonstration, the AISC AM Exploratory Task Force will further document and disseminate the lessons learned from the design, fabrication, and testing processes. One of the most significant findings will be a recommended workflow for implementing AM components in the structural steel industry.

Exciting developments for AM in the structural steel industry are progressing beyond the AM bridge. An AISC Milek Fellowship continues to explore AM for use in structural steel applications. Furthermore, draft AISC *Specification* language has been prepared and balloted, paving the way for implementing AM in the structural steel industry.

Additive manufacturing offers many potential strategic benefits to the structural steel industry, including the optimization of structural components; free-form design that enhances architecturally exposed structural steel; an alternative for costly and complex fabrication; an accelerated solution for casting replacements, part consolidation, and faster connections; a novel alternative for repair and retrofit of existing infrastructure. The bridge has highlighted many of these advantages in a tangible, interactive demonstration project.

Following controlled load test completion, AISC is planning to display the bridge at conferences and trade shows throughout the country in 2026. ■





The aerial view (top) and side view (bottom) of the bridge's printed (green) and HSS (red) members, and the bridge displayed in the booth (middle). The tension rods support the bridge superstructure.

Justin Binder (**j.binder@castconnex.com**) is the engineering manager at CAST CONNEX, **Amanda Dodge** (**Amanda_Dodge@lincolnelectric.com**) is an additive engineer at Lincoln Electric, **Dave Eckmann** (**deckmann@mka.com**) is president of Magnusson Klemencic Associates, **Eloy Rodriguez** (**erodriguez@steelfab-inc.com**) is a project manager and BIM coordinator at SteelFab, and **Ryan Sherman** (**ryan.sherman@ce.gatech.edu**) is an associate professor at Georgia Tech.